Modeling hydrologic responses in a small forested watershed by a new dynamic TOPMODEL (Panola Mountain, Georgia, USA)

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Abstract

Preliminary modeling results for a new version of the rainfall-runoff model TOPMODEL, Dynamic TOPMODEL are compared to those of the Original TOPMODEL formulation for predicting streamflow at the Panola Mountain Research Watershed, Georgia. Dynamic TOPMODEL uses a kinematic wave routing of subsurface flow, which allows for dynamically variable upslope contributing areas. The performance of each model was assessed using a 30-minute time step for each of three water years (October through September: 1993, 1994, and 1998) and results were compiled for wetting up, wet, drying out, and dry periods within each year. A likelihood measure of predicted streamflow was similar for Original TOPMODEL and Dynamic TOPMODEL and depending on the year and the sub-period, the r^2 of the best models ranged from 0.5 to 0.7. Each model underpredicted the peak streamflow, and during recession generally overpredicted streamflow in wet periods and underpredicted in dry periods. During recession, however, the difference between the observed streamflow and Dynamic TOPMODEL predicted streamflow was generally less than that for the Original TOPMODEL. The distribution of transmissivity for the Dynamic TOPMODEL simulations generally is more stable, except during dry periods, than for the Original TOPMODEL simulations, i.e., a clearly defined relation exists between sum of absolute errors and mean effective lateral saturated transmissivity having a narrow band of transmissivities for minimum *SAE* simulations. The Dynamic TOPMODEL prediction bounds were broader, and the lower bound more closely follows recession streamflow than that of the Original TOPMODEL.

1 Introduction

TOPMODEL is a rainfall-runoff model in which distributed predictions of catchment response are made based on hydrological similarity of points in a catchment. The index of hydrological similarity is based on the topographic index, $ln(a/tanb)$ (KIRKBY 1975), for which a is the area draining through a point from upslope and $tanb$ is the local slope angle. The index identifies areas with greater upslope contributing area, a, and lower gradients, b, as being more likely to be saturated than areas with lower a and higher b. Implicit in this form of the index is an assumption of quasi-steady state configuration of the water table, which is parallel to the surface topography, and a spatially constant downslope transmissivity function, for which transmissivity decreases exponentially with depth. The quasi-steady state assumption implies that downslope flow occurs throughout the hillslope and is equal to averaged cumulative upslope recharge rate at each point. These quasi-steady state dynamics have been criticised (BARLING et al. 1994, BEVEN 1997, WIGMOSTA & LETTENMAIER 1999) because, where a hillslope is seasonally dry, the effective upslope contributing areas do not extend to the catchment divide. This problem, endemic to most hydrological models, causes difficulties in modeling changes in wetness, i.e., wetting up or drying out periods.

The steady state assumption of Original TOPMODEL, however, is a convenient way of simplifying the model structure, parameterization, and calculations. It is debatable if modeling results will be greatly improved in humid catchments by a more dynamic approach. The dynamics of the effective contributing area, however, may be an important control on the response in catchments where dry seasons and wetting up periods are long. Likewise, a more dynamic approach may improve runoff prediction and more accurately reflect the processes of runoff generation even in the short term in catchments in which the hydraulic characteristics change rapidly while drying out or wetting up.

Dynamic TOPMODEL, a new version of TOPMODEL, extends the Original TOPMODEL quasi-steady state assumptions in that the hydrological flux is individually accounted and routed spatially between areas of defined hydrological similarity. In its simplest form, the basic concept of a spatial index (i.e., that which defines the hydrological similarity), derived from upslope contributing areas and local slope angle, is maintained. The flux between hydrologically representative (or similar) units (HRUs) is calculated individually using kinematic wave equations (BEVEN & FREER, in press). This allowance for local accounting of soil moisture status and fluxes enables the modelled catchment areas to be flexible in their dynamic response. There is no longer a need to identify a global function of hydrological fluxes for each HRU as was required within the Original TOPMODEL form. Furthermore, local accounting and routing introduces the possibility of a dynamic subsurface contributing area, in that downslope flux needs only to be maintained where recharge is sufficient to induce downslope saturated flow during a time step.

The objectives of this paper are to evaluate the results of Dynamic TOPMODEL and compare them with those of the Original TOPMODEL on a forested, seasonally dry catchment, the Panola Mountain Research Watershed, Georgia, USA.

1.1 Study site

The Panola Mountain Research Watershed (PMRW) is a 41-ha forested catchment, 25-km southeast of Atlanta, Georgia, USA Atlanta (84°10'W, 33°37'N). The watershed is 93 % forested, consisting of hickory, oak, tulip poplar, and loblolly pine, and 7 % partially vegetated (lichens and mosses) bedrock outcrops, of which a 3-ha outcrop in the southwest part of the watershed is the largest outcrop. Relief is 56 m and hillslopes average 18%. Soils are predominantly ultisols developed in colluvium and residuum intergrading to inceptisols developed in colluvium, recent alluvium, or in highly eroded landscape positions. Typical soil profiles are 0.6 to 1.6 m thick grading into saprolite. The regolith typically is 0 to 5 m thick, which thins from the valley bottoms to the ridge tops.

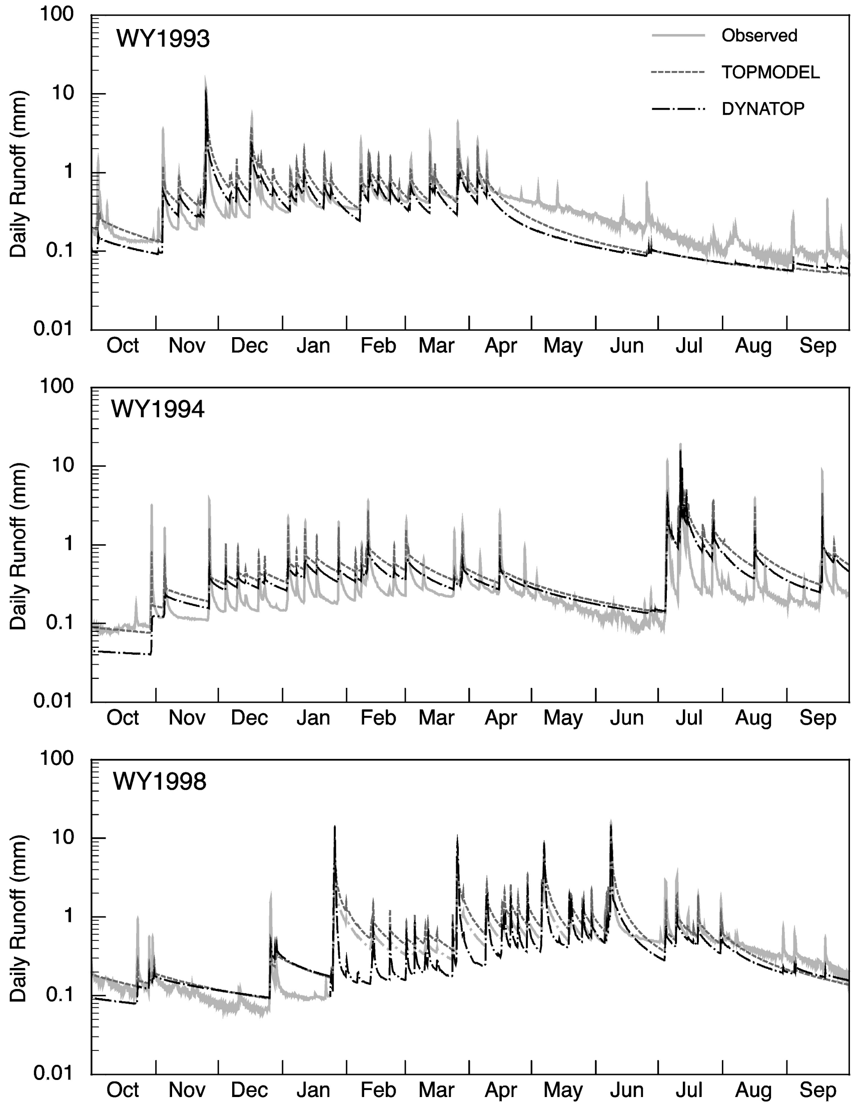

Fig. 1 Observed and the mean predicted model streamflow (runoff) for TOPMODEL and Dynamic TOPMODEL from the Panola Mountain Research Watershed, Georgia. The mean was determined from the weighted mean predicted values for models having likelihood measures greater than 0.6 for WY1993 and WY1998 and 0.5 for WY1994

A long growing season, warm temperatures, and a high percentage of possible sunshine result in a high evapotranspiration demand. From 1984 to 1999, average annual runoff was 33 % of average annual precipitation (1,225 mm with less than 1 % snow). During the summer from May through September, rainstorms are convective, whereas during the remainder of the year precipitation is dominated by synoptic weather systems. Streamflow is flashy and is attributable to runoff generated from bedrock outcrops in the headwaters. Although streamflow decreases rapidly during recession, baseflow is sustained throughout the year, even during droughts.

2 Methods

The catchment was divided into approximately 80 HRUs based on the topographic index (a 2-dimensional matrix of upslope accumulated area and local slope angle was used to define HRUs) for the model comparison. Also for the analysis herein, the HRUs were not further subdivided based on other PMRW characteristics that may define hydrologic (or hydrochemical) variability.

Model performance was assessed using the Generalised Likelihood Uncertainty Estimation (GLUE) procedure (BEVEN & BINLEY 1992, FREER et al. 1996, BEVEN & FREER in press). The GLUE procedure is a Monte Carlo based technique that allows for the concept of equifinality of parameter sets in the evaluation of modeling uncertainty (BEVEN 1993). The predictions of different parameter sets were evaluated with respect to predictions of the PMRW streamflow time series using the likelihood measure. For both the Original TOPMODEL and Dynamic TOPMODEL, parameter values within the range listed in Table 1 were randomly selected using uniform sampling distributions for 100,000 simulations for each of three annual periods, water years (WY: October through September) 1993, 1994, and 1998. Each period cycles through high and low soil-moisture deficits, during which the effective upslope contributing areas were expected to vary significantly from those suggested by the steady-state assumptions of the original model. The timing of the cycles varied among the periods (Fig. 1).

Evaporation estimates were calculated from automatic weather station data using a Penman-Monteith equation. Both models used the same root zone and unsaturated zone model structures, requiring minimal additional parameters, as described in BEVEN et al. (1995). The dynamics of the saturated zone stores for both models assumed an exponential decline in hydraulic conductivity with depth.

Tab. 1 Parameter ranges for Original TOPMODEL and Dynamic TOPMODEL

Parameter	Description	Model*	Range
SZM [m]	Form of the exponential decline in conductivity	1,2	0.01 - 0.08
$ln(T_0)$ [m^2 h^{-1}]	Effective lateral saturated transmissivity	1,2	-7 - 1
SR_{max} [m]	Maximum root zone storage	1,2	0.015 - 0.1
SR_{init} [m]	Initial root zone deficit	1,2	0.0 - 0.05
CHV [m h^{-1}]	Channel routing velocity	1,2	1000 - 5000
T_d [m h^{-1}]	Unsaturated zone time delay per unit deficit	1,2	0.1 - 120
S_{max} * [m]	Maximum effective deficit of subsurface saturated zone	2	0.2 - 2

*1: Original TOPMODEL

2: Dynamic TOPMODEL

3 Results and discussion

According to the likelihood measure, the models performed similarly (Fig. 1 and Tab. 2). The number of simulations exceeding the threshold likelihood measure of 0.6 for WY1993 and WY 1998 and 0.5 for WY1994 for Original TOPMODEL were significantly greater than for the Dynamic TOPMODEL, particularly for WY1993 and WY1998. These numbers are skewed, however, due to difficulties in adequately sampling the parameter values in Dynamic TOPMODEL. In particular, the skew is due to the interaction of the S_{max} in relation to the water table initialization and dynamics expressed by parameters $ln(T_0)$ and *SZM*. Using uniform uncorrelated sampling strategies results in a significant percentage of model simulations with near zero discharge dynamics as the water table dynamics rarely develop above the S_{max} threshold. Therefore, these statistics are not strictly comparable for assessing model performance.

The models, on average, overpredicted the winter wet-period recession streamflow, and underpredicted the summer dry-period recession streamflow for WY1993 and WY1998 (Fig. 1). In WY1994, summer streamflow was atypical, in that the wettest month of record occurred during July 1994, resulting from Tropical Storm Alberto. Precipitation during July 1994 was greater than 450 mm and runoff was greater than 120 mm, which exceeds the total summer runoff (June through September) for any year since monitoring began in 1985. The models generally predicted the correct timing of the stormflow response, but underpredicted the peak streamflow. The Original TOPMODEL predictions of the peak streamflow are generally higher than those of Dynamic TOPMODEL and closer to the observed; Original TOPMODEL recession flows also are higher but deviate more from the observed flows than those of Dynamic TOPMODEL (note the logarithmic scale).

Tab. 2 Summary characteristics of 100,000 simulations for Original TOPMODEL and Dynamic TOPMODEL

Measure	Original TOPMODEL			Dynamic TOPMODEL		
	WY1993	**WY1994**	**WY1998**	**WY1993**	**WY1994**	**WY1998**
Likelihood of best model fit	0.69	0.57	0.67	0.69	0.65	0.67
Number of model simulations used for extracting the mean and uncertainty in streamflow[1]	2380	173	1164	436	142	102

[1] Likelihood threshold of 0.6 for WY1993 and WY1998; 0.5 for WY1994

The likelihood measure, sum of absolute error (SAE), and simulation bias versus parameter value for a sampling (8,000 of the *best* models of the 100,000 simulations) indicated several distinct relations, particularly for $ln(T_o)$ between models and among water years and wetness periods. Behavioural simulations, however, exist throughout the parameter ranges, which is consistent with the equifinality concept that underlies the GLUE methodology (Tab. 1). In addition to separating the relations between *SAE* and $ln(T_o)$ by period and wetness type (wet and dry periods), the relations also were separated by hydrograph characteristic with respect to the timing of the predicted streamflow as occurring on either the rising or the falling limb. The relation between *SAE* and $ln(T_o)$ for the Original TOPMODEL simulations indicates that the best models for recessional flows are associated with very low transmissivity, which are higher and less distinct for the rising limb. The optimum fit, therefore, falls somewhere between these extremes as reflected by the mean predicted streamflows (Tab. 2 and Fig. 1) for which Original TOPMODEL underpredicts rising limb streamflow and overpredicts recession streamflow. The Original TOPMODEL and Dynamic TOPMODEL relations for the wet period of each year are similar to those for the entire year. The best simulations of the Dynamic TOPMODEL have lower transmissivities than that of Original TOPMODEL, reflecting the suggestions of BEVEN (1997) and WIGMOSTA & LETTENMAIER (1999) that the explicit incorporation of the dynamics should result in lower effective transmissivities.

The relation between *SAE* and $ln(T_o)$ for Dynamic TOPMODEL during the wet period is very distinct, with a pronounced minimum *SAE* for each period and each year. The Dynamic TOPMODEL relation for the dry period, however, does not show a distinct minimum; this is consistent with the types of responses observed in the watershed. During the dry period, soils that are clay rich can crack with the size of the cracks varying markedly spatially. Furthermore, soil cracks can swell rapidly during storm events, which affects the infiltration rates temporally both during individual rainstorms and among rainstorms. Analyses of short-term hydrometric measurements, solute concentrations of precipitation, throughfall, soil water, groundwater and streamwater, and associated temperature variations (RATCLIFFE et al. 1996, PETERS & RATCLIFFE 1998) show that water and solutes can be rapidly transported through the soil, particularly during dry periods. After stormflow recedes, streamflow, which contains high concentrations of solutes derived from weathering, is sustained. Also, a laboratory experiment, which included the use of tracers on large, nearly undisturbed soil cores under antecedent wet conditions, shows that preferential flow occurs in the soils, and that water and solute transport is faster from more clay-rich ridge-top soils than from hillslope soils (MCINTOSH et al. 1999).

The uncertainty bounds, which were derived from the best models (Tab. 2), differ between the Original TOPMODEL and the Dynamic TOPMODEL (Fig. 2). In general, the prediction bounds for Dynamic TOPMODEL are broader and span the observed data more effectively than those of the Original TOPMODEL, possibly as a consequence of the subsurface saturated zone dynamics being better reproduced. The lower Dynamic TOPMODEL prediction bound for streamflow recessions are the most similar to the actual recession streamflows primarily during the winter wet periods than is the lower Original TOPMODEL prediction bound, which likewise suggests a better representation of the subsurface dynamics than in the Original TOPMODEL. Additional analysis of the Dynamic TOPMODEL spatial predictions, with respect to the conceptualization of hydrological processes at PMRW, is required to determine if the Dynamic TOPMODEL structure is a better representation than that of Original TOPMODEL. Even if Dynamic TOPMODEL is a more physically representative model, additional analysis and model development in a more distributed manner will probably be required to better predict streamflow at PMRW. It is apparent from the analysis herein that the simple model structures of Original TOPMODEL and the basic form of the Dynamic TOPMODEL are not sufficient to predict flow with only one group of HRUs. This result is consistent with the field observations of rapid flow generated from the bedrock outcrop, the highly variable ephemeral flow from the shallow soils on the hillslope, and the sustained ground-water discharge from the riparian zone. A more distributed approach using two and possibly three groups of HRUs having different functional responses (e.g., bedrock outcrop, shallow hillslope, and deeper riparian zone) will probably be required to produce a *better* predictive model of streamflow. In particular, the model should accurately reproduce the rapid streamflow response associated with runoff from the bedrock outcrops and the variable recession response due to changing soil hydraulic characteristics associated with the wetting and drying of the soils and hydrological linkages with the hillslopes.

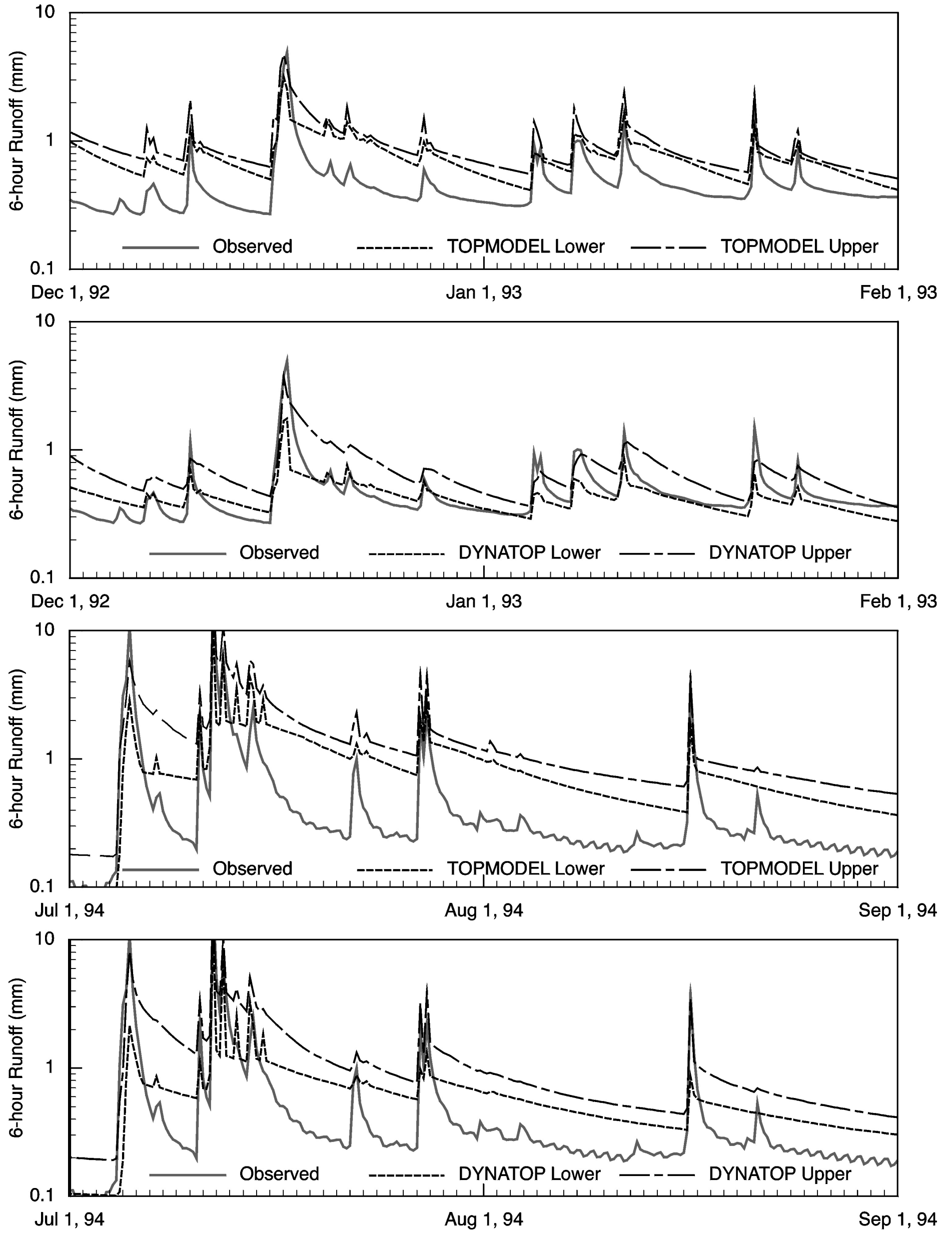

Fig. 2 Observed and the lower (5 %) and upper (95 %) uncertainty bounds of predicted 6-hour runoff from the best (Tab. 2) TOPMODEL and Dynamic TOPMODEL simulations for a wet period, December through January 1992, and a dry period, July through September 1994

Acknowledgment

The study was conducted in cooperation with the Georgia Department of Natural Resources. The authors are grateful to the U.S. Geological Survey staff for the Panola Mountain Research Project, and in particular, for the database support by B. T. Aulenbach. The research was supported by the U.S. Geological Survey's Water, Energy, and Biogeochemical Budgets Program, the U.S. National Science Foundation (EAR 9743311), and the U.K.'s National Environmental Research Council (GR3/11450).

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